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(54) Q-switched fibre laser

(57) A Q-switched fibre laser system comprising a doped fibre gain medium 2 that is continuously pumped by a pump source 6. Back reflection within the system is insufficient to support continuous wave lasing because reflection from the output end is suppressed. A light storage means 8, such as a fibre loop, is coupled to the doped fibre gain medium and gathers light produced by spontaneous decay from the excited state. This gathered light generates back reflected light through a distributed back scattering, such as Rayleigh scattering. The back scattered light is resonated in a loop, and provides a delayed nonlinear feedback into the doped fibre. As the population inversion increases, then the amount of light stored within the light storage means 8 increases until the back scattering reaches a threshold amount that is sufficient to stimulate a pulse of laser light within the doped fibre gain medium 2. An optical isolator 10 and/or a cleaved end face 12 may be used at one end of the laser cavity to inhibit continuous wave lasing. As an alternative to the fibre loop 8, a length of single mode fibre 14 may be used, or for self Q-switching, feedback may also be achieved as result of back scattering from the doped fibre itself. The Q-switched fibre laser produced results in pulses of laser light sufficiently intense to result in a frequency supercontinuum. Repetition rate may be controlled by controlling the pump output of the pump source 6. The repetition rate may be stabilised by modulating the pump output.

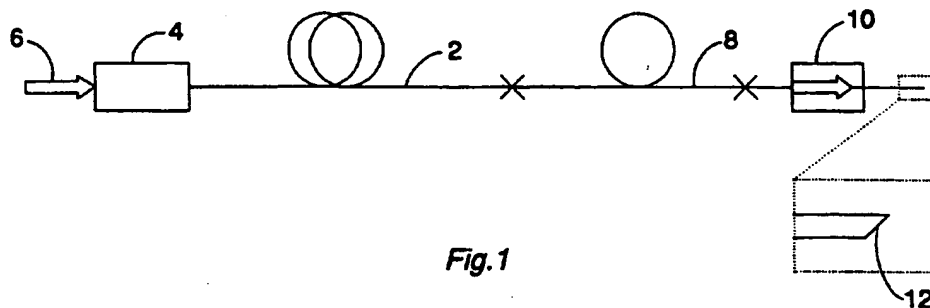


Fig.1

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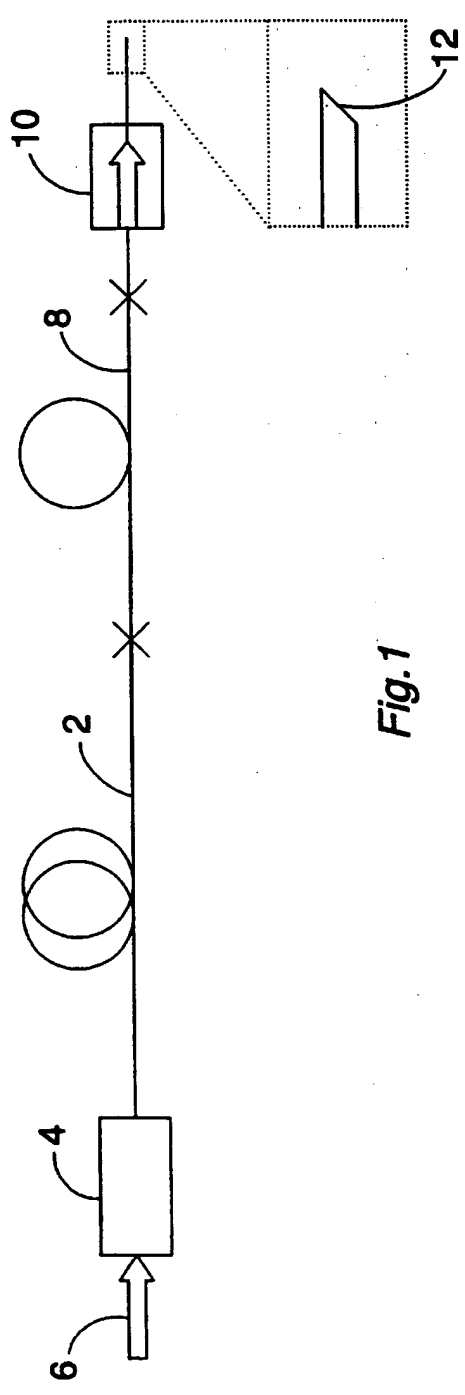


Fig.1

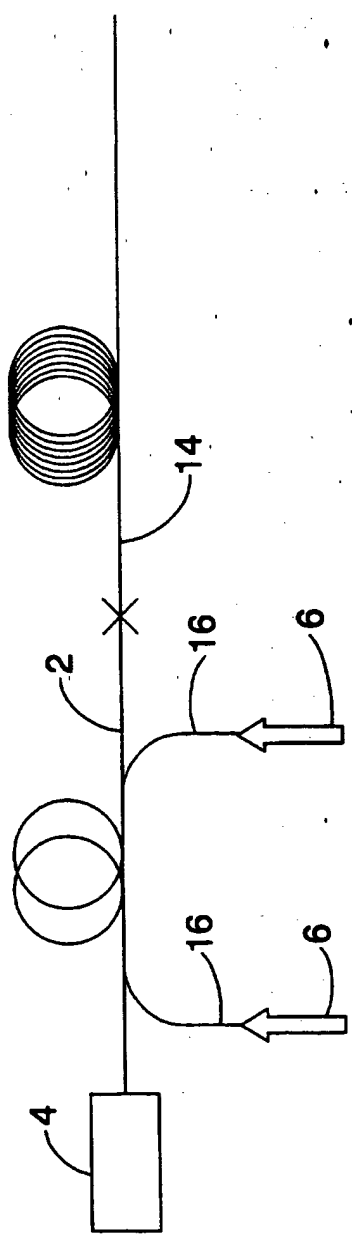


Fig.2

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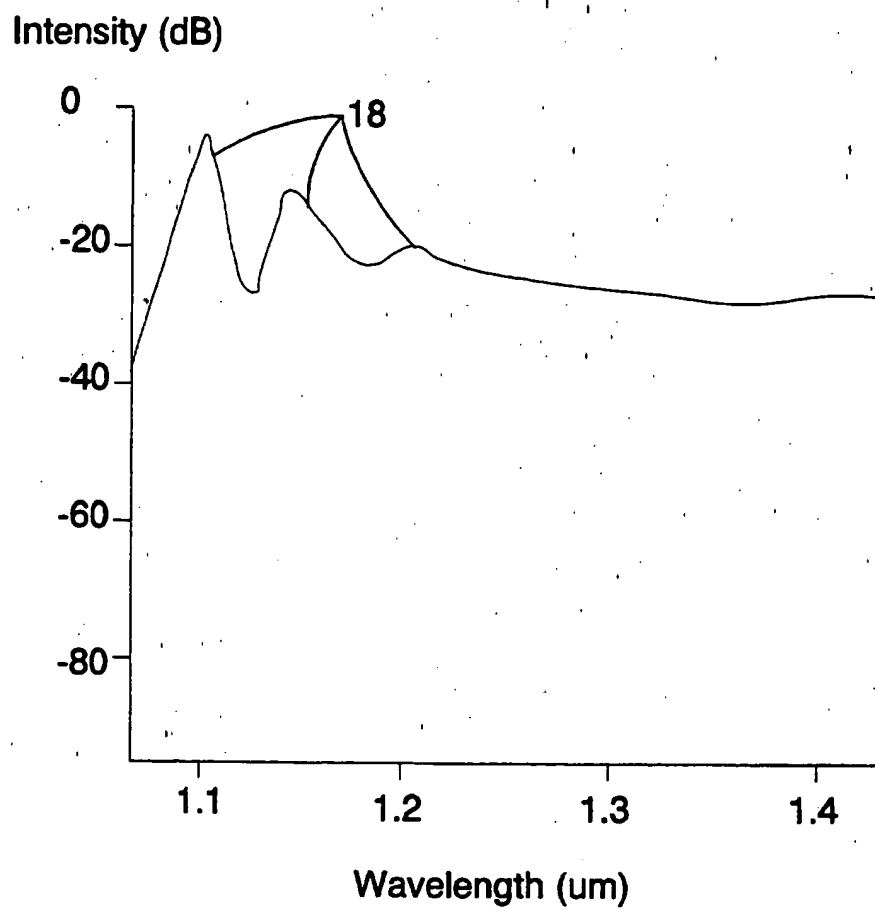


Fig.3

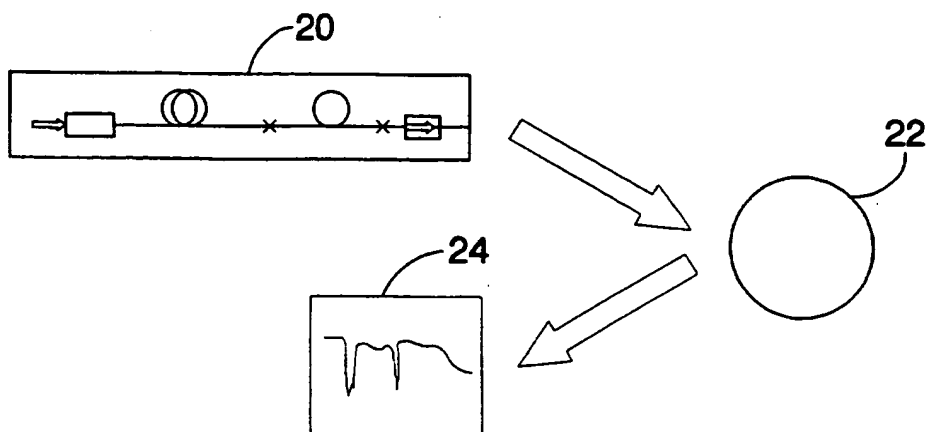


Fig.4

Q-SWITCHED FIBRE LASER

This invention relates to Q-switched fibre lasers.

5 The technique of Q-switching is known in bulk and fibre laser systems. If, the Q of the laser resonator (energy stored per pass/energy dissipated per pass) is kept low, generally by including some optical element such that loss occurs, then laser action is inhibited. Consequently, with continued pumping to populate an excited state, the population inversion in the lasing transition increases. If the Q is then rapidly restored, then the large population inversion that has been built up gives rise to an high intensity pulse of laser light which rapidly depletes the inversion (a so-called Q-switched pulse).

10 It is known to actively switch the Q of a laser system using an electro-optic or acousto-optic switch.

Passive techniques for Q-switching may also be used. An example of such a passive technique is the use of a saturable absorber. The absorber suppresses the Q of the system until it is saturated whereupon the Q is restored and a pulse of laser light is generated.

Known Q-switched laser sources suffer from a number of technical problems. The relative complexity of the Q-switching mechanism, particularly in the case of electro-optical and acousto-optic switches, increases the cost of the devices. In addition, such Q-switches are relatively fragile making the lasers unsuitable for use in harsh environments. Furthermore, such lasers can be relatively large, heavy and energy inefficient, so restricting their portability. The above problems are particularly the case when a high output power is desired.

25 Viewed from one aspect the present invention provides a Q-switched fibre laser comprising:

- a doped fibre gain medium forming at least a portion of a lasing cavity;
- a pump source for pumping said doped fibre gain medium to populate an excited state;

- light storage means for gathering from and back scattering into said lasing cavity light emitted from said doped fibre medium due to spontaneous decay from said excited

state;

wherein back reflection within said lasing cavity is insufficient to produce continuous wave lasing and, as said doped fibre gain medium is pumped, said back scattering increases as light stored within said light storage means increases until said back scattering exceeds a threshold amount that stimulates a pulse of laser light to be generated in said lasing cavity after which said back scattering is again below said threshold amount.

The invention uses a new mechanism to passively alter the Q of the laser and stimulate pulses of laser light. The gain per pass is sufficiently high within a doped fibre gain medium that back scattered light can be made to stimulate laser action. In operation, the pump source pumps the doped fibre gain medium to populate the excited state. As the population of the excited state increases, the population inversion increases, and the amount of light emitted from spontaneous decay of the excited state also increases. As the emitted light propagates along the fibre, it is back scattered providing a feedback to the laser. The amount of back scattering is determined by the intensity of the emitted light and the effective length of the fibre over which the light has propagated from the start of the cycle. The magnitude of the feedback increases with time as the light propagates further along the fibre. This results in a nonlinear and time dependent increase in laser feedback. As the gain in the fibre laser amplifier increases, the amount of the feedback from back scattered from the fibre increases until it exceeds a threshold sufficient to cause laser action and generate a Q-switch pulse. The dynamic pulse formation is fast, and the threshold is exceeded for a short period of time, resulting the generation of a short giant pulse. The Q-switch pulse is amplified propagating through all the length of the fibre laser, extracting the energy stored in the cavity in the form of the population inversion. This depletes the upper lasing level, and thus gives rise to a repetitive operation of the laser.

This new technique for Q-switching a laser enables devices to be produced having significant size, cost, robustness and power efficiency advantages over the prior art with the ability to produce high output powers.

The light storage means (distributed feedback means) could take a number of

different forms providing it has the function of gathering light from and back scattering light into the laser cavity (feedback may even be achieved as a result of back scattering from the doped fibre itself). However, in preferred embodiments of the invention said light storage means comprises a fibre loop coupled to said laser cavity such that a proportion of said light emitted from said doped fibre medium due to spontaneous decay from said excited state enters said fibre loop and is trapped circulating therein and building up in intensity until said back scattering from said fibre loop stimulates said pulse of laser light.

The loop enhances the feedback and makes it stable. The use of a fibre loop coupled to the laser cavity to perform the function of the light storage means also produces a laser incorporating fibre components to a greater extent. Such an arrangement is particularly compact and robust.

In operation, a proportion of the light produced by the spontaneous decay is coupled into the fibre loop where it is trapped and continues to circulate therein. As the population inversion within the doped fibre gain medium continues to grow, light continues to be produced due to spontaneous decay with a proportion of this light being coupled into the fibre loop. This continual gathering of light into the fibre loop causes the intensity of the light circulating within the fibre loop to increase. As the intensity of circulating light increases, then the amount of light back scattered into the laser cavity from the fibre loop, due to processes such as Rayleigh scattering, increases. Eventually the level of the back scattered light reaches a threshold amount that is sufficient to stimulate a pulse of laser light within the high gain per unit length doped fibre gain medium. Once this pulse of laser light has been generated, the population inversion is depleted until it is repumped. With this removal of the population inversion, the gain is dramatically reduced and the light circulating within the fibre loop relatively rapidly diminishes, and the spontaneous emission decreases.

Other geometries are possible for the light storage means. A further preferred geometry is that in which said light storage means comprises a length of single mode fibre coupled to an end of said laser cavity such that said light emitted from said doped

fibre medium due to spontaneous decay from said excited state enters said length of single mode fibre and propagates therethrough until said excited state is sufficiently populated that the intensity of said light emitted from said doped fibre medium due to spontaneous decay from said excited state is sufficient to result in said back scattering from said length of single mode fibre stimulating said pulse of laser light.

The use of a length of single mode fibre as the light storage means also produces a higher proportion of fibre components so leading to improved robustness and compactness. In this embodiment, light produced due to spontaneous decay from the excited state enters the single mode fibre and propagates therethrough. As the population inversion increases, the amount of light entering the single mode fibre increases and the amount of light being back scattered from the single mode fibre also increases. Eventually, the amount of back scattered light reaches the threshold amount that is sufficient to cause Q-switching.

It will be appreciated that the light storage means could be either directly or indirectly coupled to the doped fibre gain medium. However, simplicity, compactness and robustness is increased when said light storage means is directly coupled to said doped fibre gain medium.

Whilst the use of fibres to provide the light storage means increases the proportion of fibre components making up the system, it is still more preferable that the laser should be made to have an all fibre configuration.

Various pump sources may be used providing that they serve to populate the excited state. However, a laser diode is particularly suited for use in the present system since its inherently compact and robust nature complement the other aspects of the system.

An additional degree of control over the system is provided in embodiments in which mean pumping output of said pump source is controlled to vary repetition rate of said pulse of laser light.

Whilst controlling the mean pumping output of the pump source does vary the repetition rate of the pulse of laser light, this repetition rate is somewhat unstable. This instability may be addressed in embodiments of the invention in which pumping output

of said pump source is synchronously modulated to stabilise repetition rate of said pulse of laser light.

5 The Q-switching of the system in accordance with the invention can produce laser pulses of a variety of intensities depending upon the degree of population inversion that must be achieved to result in back scattering sufficient to stimulate a pulse of laser light. However, the high gain of the doped fibre gain medium may be utilised to produce a system in which said back scattering stimulates said pulse of laser light when said excited state has a population that leads to an intensity of said pulse of laser light such that said pulse of laser light is a frequency supercontinuum due to non linear Raman self
10 conversion within said laser cavity, generating a supercontinuum spectrum.

The production of a frequency supercontinuum within high intensity, short duration pulses yields properties that can be advantageous in many systems. It is more usual to consider a laser continuously producing light of a particularly narrow frequency spectrum.

15 The dopant used within the doped fibre gain medium can be one of many possibilities providing that a sufficient population inversion and gain per unit length can be achieved. Ytterbium and Erbium have been found to be particularly suited to these requirements, but any rare earth element may be used.

Whilst the requirements of population inversion and gain per unit length may to some extent constrain the output frequency of the pulse of laser light, these constraints
20 can be overcome by using an harmonic doubler for generating higher frequency light from said pulse of laser light.

In order that a sufficient population inversion can be created within the doped fibre gain medium it is important that back reflection from external components or fibre cleaves is not sufficient to produce continuous wave lasing. A convenient way of
25 achieving this is that said laser cavity is terminated with an optical isolator such that said back reflection is insufficient to produce continuous wave lasing.

In order to reduce back reflection from the fibre end, it is also preferred that said laser cavity is terminated with an optical fibre having an angle end face that reduces Fresnel reflection.

30 With a suitable choice of pump source and length of fibre gain medium it has

been found possible to produce a pulse rate of 100Hz to 20Khz with a pulse duration of 5ns to 15ns.

As previously mentioned, a Q-switched fibre laser in accordance with the present invention has many potential applications. Particularly advantageous applications are within a gas analyzer, a micro machining apparatus, a laser ranging apparatus and a laser dazzler apparatus.

Viewed from another aspect the present invention provides a method of Q-switching a fibre laser having a doped fibre gain medium forming at least a portion of a lasing cavity, said method comprising the steps of:

pumping said doped fibre gain medium to populate an excited state;

gathering from and back scattering into said lasing cavity with a light storage means light emitted from said doped fibre medium due to spontaneous decay from said excited state;

wherein back reflection within said lasing cavity is insufficient to produce continuous wave lasing and, as said doped fibre gain medium is pumped, said back scattering increases as light stored within said light storage means increases until said back scattering exceeds a threshold amount that stimulates a pulse of laser light to be generated in said lasing cavity after which said back scattering is again below said threshold amount.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 illustrates one embodiment of the present invention;

Figure 2 illustrates a further embodiment of the present invention;

Figure 3 illustrates a portion of the frequency spectrum of a laser pulse produced in accordance with one embodiment of the invention; and

Figure 4 schematically illustrates the use of the present invention within a gas analyzer.

Figure 1 shows a Q-switched fibre laser. A doped fibre gain medium 2 is provided. The dopant can be Yb^{3+} or Er^{3+} , or any other rare earth. One end of the doped fibre gain medium is terminated with a reflector 4, such as a dielectric mirror, integrated

Bragg grating etc.

A pump source 6, such as a laser diode, serves to populate an excited state within the doped fibre gain medium 2 by passing pumping light through the reflector 4 into the doped fibre gain medium 2. A light storage means 8 is coupled to one end of the doped fibre gain medium 2. In this embodiment, the light storage means has the form of a 10:90 fused fibre coupled which has two of its ports coupled together to form a fibre loop, typically of a length of a few metres. The output end of the light storage means is coupled to a fibre pigtailed optical isolator 10 (with a back reflection isolation of typically 30-40 dB). Alternatively, or additionally, in order to further reduce the back reflection due to potential Fresnel reflection of the end facet of the fibre, this is cleaved at an angle to produce an angled end face 12.

As a result of the fibre pigtailed optical oscillator 10 and/or the cleaved end face 12, back reflection is insufficient to support continuous wave lasing. Radiation enters the light storage means 8 and builds up in intensity with time so gradually increasing the amount of back scattering. Initially the back scattering is insufficient to stimulate a laser pulse and the population inversion within the doped fibre gain medium 2 continues to increase. Eventually, the amount of back scattering from the light storage means 8 increases to a threshold amount (which may still be relatively small) and as a result of the high single pass gain of the doped fibre gain medium 2, laser action takes place and a pulse of laser light is generated rapidly depleting the population inversion.

Figure 2 illustrates an alternative geometry for a Q-switched fibre laser. In the embodiment of Figure 2, the light storage means takes the form of a length of single mode fibre 14. In addition, pumping through the reflector 4 is replaced by pumping through fused fibre couplers 16.

In operation, pumping proceeds to build up a population inversion within the doped fibre gain medium 2. Radiation due to spontaneous decay within the doped fibre gain medium 2 passes into the length of single mode fibre 14. A proportion of this radiation due to spontaneous decay is back scattered into the doped fibre gain medium. As the population inversion increases, then the amount of back scattered radiation increases until a threshold amount is reached that stimulates a pulse of laser light.

Figure 3 illustrates a portion of the frequency supercontinuum that may be produced with a Yb^{3+} based doped fibre gain medium 2. The initial peaks 18 within this spectrum correspond to the fundamental laser line plus orders of Raman scattering. Raman scattering continues at longer wavelength, with the peaks become less distinct. In practice, the supercontinuum observed extended beyond $2.3 \times 10^{-6} \text{m}$, which was the sensitivity limit of the detection equipment employed. A total power integrated over the whole spectrum was approximately 1W. In this way an extremely bright continuum source was provided.

The repetition rate of the pulses of laser light is controlled by the time taken for the population inversion to reach a sufficient level to result in sufficient back scattering to stimulate a laser pulse. The rate at which the population inversion increases is itself controlled by the pumping power. Thus, the repetition rate may be controlled by controlling the pumping power. The amount of back scattered light that actually stimulates laser pulse is relatively small and small random variations in the degree of back scattering produce an instability in the repetition rate. This instability may be reduced by modulating the pumping power. Modulation of a laser diode 6 being used as a pump source is relatively straightforward and convenient.

The Yb^{3+} and Er^{3+} doped fibres can produce high efficiency in the infra-red. Such infra-red light pulses may be converted to visible wavelengths using an harmonic doubler. Such extremely bright continuum pulses in the visible range are well suited to producing a laser dazzler. The compact, highly efficient and robust nature of the system further complement this application.

Figure 4 schematically illustrates the use of the Q-switched fibre laser of the present invention within a gas analyzer. A pulse source 20 produces light pulses having a frequency supercontinuum in the infra-red that are directed to a gas sample 22. The light that is returned from the gas sample 22 is passed to a spectrometer 24 where the absorption characteristics over the infra-red range can be measured to determine the content of the gas sample 22.

The compact, highly efficient and robust nature of the Q-switched fibre laser of the invention also make it highly suitable for use within a laser ranging apparatus or a

micromachining apparatus.

The invention may also be viewed in a broad sense as providing a self-Q-switched fibre laser based upon distributed back scattering.

5 The described Q-switching mechanism can appear in different fibre lasers and amplifiers. This may result in the generation of giant pulses which may cause the damage of the pump diodes. This negative effect can be suppressed by reducing the leakage of the signal into pump lasers, reducing the total length of the fibre laser or amplifier, or, in the case of a laser, increasing the laser feedback above the threshold of distributed back scattering Q-switching.

CLAIMS

1. A Q-switched fibre laser comprising:

a doped fibre gain medium forming at least a portion of a lasing cavity;

5 a pump source for pumping said doped fibre gain medium to populate an excited state;

light storage means for gathering from and back scattering into said lasing cavity light emitted from said doped fibre medium due to spontaneous decay from said excited state;

10 wherein back reflection within said lasing cavity is insufficient to produce continuous wave lasing and, as said doped fibre gain medium is pumped, said back scattering increases as light stored within said light storage means increases until said back scattering exceeds a threshold amount that stimulates a pulse of laser light to be generated in said lasing cavity after which said back scattering is again below said
15 threshold amount.

2. A Q-switched fibre laser as claimed in claim 1, wherein said light storage means comprises a fibre loop coupled to said laser cavity such that a proportion of said light emitted from said doped fibre medium due to spontaneous decay from said excited state
20 enters said fibre loop and is trapped circulating therein and building up in intensity until said back scattering from said fibre loop stimulates said pulse of laser light.

3. A Q-switched fibre laser as claimed in claim 1, wherein said light storage means comprises a length of single mode fibre coupled to an end of said laser cavity such that
25 said light emitted from said doped fibre medium due to spontaneous decay from said excited state enters said length of single mode fibre and propagates therethrough until said excited state is sufficiently populated that the intensity of said light emitted from said doped fibre medium due to spontaneous decay from said excited state is sufficient to result in said back scattering from said length of single mode fibre stimulating said pulse
30 of laser light.

4. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said light storage means is directly coupled to said doped fibre gain medium.

5. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said Q-switched fibre laser has an all fibre configuration.

6. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said pump source is a laser diode.

7. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein mean pumping output of said pump source is controlled to vary repetition rate of said pulse of laser light.

8. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein pumping output of said pump source is synchronously modulated to stabilise repetition rate of said pulse of laser light.

9. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said back scattering stimulates said pulse of laser light when said excited state has a population that leads to an intensity of said pulse of laser light such that said pulse of laser light is a frequency supercontinuum due to non linear self conversion within said laser cavity.

10. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said doped fibre gain medium is doped with one of ytterbium and erbium.

11. A Q-switched fibre laser as claimed in any one of the preceding claims, comprising an harmonic doubler for generating higher frequency light from said pulse of laser light.

12. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said laser cavity is terminated with an optical isolator such that said back reflection is insufficient to produce continuous wave lasing.

5 13. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said laser cavity is terminated with an optical fibre having an angle end face that reduces Fresnel reflection.

10 14. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said pump source has a mean pump output yielding a pulse rate of 100Hz to 20kHz.

15 15. A Q-switched fibre laser as claimed in any one of the preceding claims, wherein said doped fibre gain medium has a length yielding a pulse duration of 5ns to 15ns.

15 16. A gas analyzer comprising:
a Q-switched fibre laser as claimed in any one of claims 1 to 15 producing pulses of laser light having a infrared frequency supercontinuum;
means for directing said pulses of laser light through a gas sample;
means for spectroscopically measuring absorption of said pulses of laser light
20 through said gas sample to determine gas composition.

17. A micro machining apparatus comprising a Q-switched fibre laser as claimed in any one of claims 1 to 15.

25 18. A laser ranging apparatus comprising a Q-switched fibre laser as claimed in any one of claims 1 to 15.

19. A laser dazzler apparatus comprising a Q-switched fibre laser as claimed in any one of claims 1 to 15.

20. A method of Q-switching a fibre laser having a doped fibre gain medium forming at least a portion of a lasing cavity, said method comprising the steps of:

pumping said doped fibre gain medium to populate an excited state;

gathering from and back scattering into said lasing cavity with a light storage

5 means light emitted from said doped fibre medium due to spontaneous decay from said excited state;

wherein back reflection within said lasing cavity is insufficient to produce continuous wave lasing and, as said doped fibre gain medium is pumped, said back scattering increases as light stored within said light storage means increases until said
10 back scattering exceeds a threshold amount that stimulates a pulse of laser light to be generated in said lasing cavity after which said back scattering is again below said threshold amount.

21. A Q-switched fibre laser substantially as hereinbefore described with reference
15 to the accompanying drawings.

22. A method of Q-switching a fibre laser substantially as hereinbefore described with reference to the accompanying drawings.



The Patent Office

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Claims searched: 1-22

Examiner: David Mobbs
Date of search: 29 March 1996

Patents Act 1977 Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK CI (Ed.O): H1C CBAA, CBAX, CCX, CEX.

Int CI (Ed.6): H01S 3/06, 3/11.

Other: ONLINE: CLAIMS, INSPEC, JAPIO, WPI.

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
	NONE.	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.